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THE SPINNING OF AIRCRAFT - A DISCUSSION OF SPIN PREDICTION TECHNIQUES INCLUDING A CHRONOLOGICAL BIBLIOGRAPHY (U)

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SUMMARY

Aircraft spinning is an important area of design for general aviation and military aircraft, and has been so, since the early days of aviation. In many of the major aeronautical laboratories in the world, aircraft spinning has been the subject of intensive periods of research. However, the resulting design criteria are still only adequate for predicting gross trends in aircraft spin behaviour. To enable flight testing to proceed with confidence and to minimise modifications during flight development most major aircraft development programmes include extensive scale-model spin testing. In this paper, the development of these techniques and their application for spin prediction will be discussed. In current military aircraft stability augmentation systems add further considerations for high angle-of-attack and spin behaviour. These and future considerations of thrust vectoring for aircraft control at high angles-of-attack are outside the scope of this paper.

DSTO ARL
MELBOURNE

POSTAL ADDRESS: Director, Aeronautical Research Laboratory,
P.O. Box 4331, Melbourne, Victoria, 3001, Australia

CONTENTS

NOTATION

b	Wing span
$\bar{c}$	Wing mean aerodynamic chord
g	Acceleration due to gravity
m	Aircraft mass
p	Body-axes roll rate
q	Body-axes pitch rate
r	Body-axes yaw rate
C_D	Drag coefficient
C_L	Lift coefficient
C_R	Total force coefficient $\sqrt{C_L^2 + C_D^2}$
C_l	Rolling moment coefficient, Rolling Moment / $(1/2\rho V^2 S_w b)$ positive clockwise looking forward
C_m	Pitching moment coefficient, Pitching moment / $(1/2\rho V^2 S_w \bar{c})$ positive nose up
C_n	Yawing moment coefficient, Yawing Moment / $(1/2\rho V^2 S_w b)$ positive nose to the right
I_X, I_Y, I_Z	Moments of inertia about the X, Y and Z body axes, respectively
R_S	Spin radius measured from spin axis to aircraft center of gravity
S	Wing area
V	Free-stream velocity
α	Angle of attack, deg.
β	Angle of slideslip, deg.
δ_a	Aileron deflection
δ_e	Elevator deflection
δ_r	Rudder deflection
ρ	Air density
σ	Inclination of flight path to the vertical
Ω	Angular velocity about spin axis, rad/sec, positive for clockwise rotation when looking into the relative wind.
$\Omega b/2V$	Spin coefficient, same sense as Ω

1. INTRODUCTION

Aircraft spinning is an important area of design for general aviation and military aircraft, and has been so, since the early days of aviation. In many of the major aeronautical laboratories in the world, aircraft spinning has been the subject of intensive periods of research. However, the resulting design criteria are still only adequate for predicting gross trends in aircraft spin behaviour. To enable flight testing to proceed with confidence and to minimise modifications during flight development most major aircraft development programmes include extensive scale-model spin testing. In this paper, the development of these techniques and their application for spin prediction will be discussed. In current military aircraft stability augmentation systems add further considerations for high angle-of-attack and spin behaviour. These and future considerations of thrust vectoring for aircraft control at high angles-of-attack are outside the scope of this paper.

Following a discussion of the nature of the spin, a summary of the historical development of spin research is presented. The methods currently available to the aircraft designer for spin prediction are discussed and some recent research at the Aeronautical Research Laboratories (ARL) in the modelling of the flight dynamics of the aircraft spin will be described.

2. THE NATURE OF THE SPIN

2.1 Spin Phases

The spin manoeuvre has traditionally been divided into four stages (Figure 1): Spin entry, incipient spin, steady spin, and spin recovery. Spin entry from unstalled flight may be deliberate - usually as a training rather than an operational manoeuvre - or inadvertent - occurring usually during low speed manoeuvres.

A deliberate spin is initiated by slowing the aircraft towards the stall and then at the point of stall generating a rate of yaw by applying full rudder deflection. The yawing motion promotes stalling and a large loss of lift due to increased flow incidence on the rearward travelling wing, while maintaining attached flow due to reduced flow incidence on the forward travelling wing. The resulting differential lift produces a rolling moment in the direction of the rearward travelling wing, and initiates the spin manoeuvre with a large rate of roll.

Aircraft with high 'spin resistance' generally require vigorous and precise control movements to initiate the spin. In contrast, inadvertent 'spin entry' can result with aircraft which are susceptible to spinning either during steep turns at low speeds, or during the low speed portions of aerobatic manoeuvres such as at the top of a loop or barrel roll.

The 'incipient spin' is the transition between 'spin entry' and the 'steady spin'. Recovery from an inadvertent spin is most effectively achieved in this phase, so it is important for pilots to be able to recognise the manoeuvre and to apply appropriate recovery action. The incipient phase is considered to end when the airspeed has become steady and a vertical trajectory has been reached. For practical purposes, the 'steady spin' is reasonably well established after two to three turns.

During the 'incipient spin' the aircraft flight path changes from horizontal to vertical, the angle-of-attack increases to well beyond the stall value, and the rotation in yaw increases to match or frequently exceed that in roll.

In the 'steady spin' or 'equilibrium spin' the aircraft describes a steep spiral motion about a vertical axis, in which spin rate, angle-of-attack, sideslip angle and vertical velocity are constant. In many cases the motion does not reach a steady equilibrium state, but may exhibit an oscillation about the nominal equilibrium point, with a frequency higher than the spin rate.

"Spin Recovery" for conventional low-speed aircraft is achieved primarily by the use of full rudder deflection to arrest the large rate of yaw. A standard technique taught during flight training for spin recovery is to centralise the ailerons, in conjunction with application of full recovery rudder and then to move the elevator control forward to regain flying speed.

Quite large variations on this technique may occur for aircraft of different inertia distribution and aerodynamic design. For modern combat aircraft in which the pitch inertia is much greater than the roll inertia application of in-spin aileron and aft elevator control results in an inertia yawing moment which favours recovery. Conversely for wing-heavy aircraft in which the roll inertia exceeds the pitch inertia the use of out-spin aileron favours recovery.

2.2 THE STEADY SPIN

The 'steady spin' phase is of particular importance since it represents a stable equilibrium flight condition from which recovery may be impossible. Because the motion is steady, it is also more tractable to analysis than the other phases.

Some aircraft exhibit more than one 'steady spin' condition or mode, in which case the sequence of control movements applied during the entry and incipient phases will determine which of the modes is reached. However, the characteristics, of the mode depend only on the aircraft aerodynamic and inertia characteristics and on the control settings. There is also a dependency on air density and hence altitude, but this will not be discussed here.

From stability considerations, the 'steady spin' may be referred to as a point of stable equilibrium similar to a trimmed condition in level flight. Figure 2 shows this condition and also another stable equilibrium, the 'deep stall'.

All these cases are in equilibrium since in each there is a balance of forces and moments about all axes; the steady spin is the most complex in that the balance occurs in the presence of large angular rotations about the roll and yaw axes.

The key to spin recovery is to design the aircraft with sufficient control power to unlock this stable condition.

The dynamics of the 'steady spin' were understood and described in detail many years ago. A comprehensive description is given by Gates and Bryant in Reference 1 in 1926 (also bibliography 1920-1929/8) As with other branches of flight dynamics, the most difficult problems associated with an analysis of the spin arise not from the system dynamics, but from the complexity of the aerodynamic forces. The more important aerodynamic forces acting in the steady spin are briefly described below.

2.3 THE BALANCE OF FORCES AND MOMENTS

Figure 3 from Ref. 1 shows that the balance of forces in a 'steady spin' is such that the drag is equal to the weight and the lift is equal to the centrifugal force. In the steady spin, the spin radius is only of the order of a few feet, the resultant force is almost normal to the wing and acts approximately at the wing semi-chord, and the normal acceleration is low.

In practice the actual balance is slightly more complex in that aerodynamic sideforces exist such that the lateral axis is not necessarily horizontal but may be tilted . The amount of tilt is directly related to the spin helix angle and to the angle of sideslip adopted in the spin. The sideslip is determined primarily by the rolling moment characteristics as will be explained later.

To illustrate the balance of moments in a 'steady spin' the primary aerodynamic contributions will be discussed. Rotary-balance data measured on a low - speed basic training aircraft with standard layout will be used to illustrate the discussion. The moments are referred to aircraft body axes. Because of the large variation in onset flows over a spinning aircraft, the choice of axis system has little significance. The less important aerodynamic contributions are neglected in this discussion but are described in detail in Ref.1.

Equilibrium of pitching moments is reached when the nose-down aerodynamic moment is equal to the large nose-up inertia moments, as shown in figure 4. The aerodynamic contributions are from the wing normal force which, for a stalled wing, acts at the wing semi-chord and from the tailplane normal force. The equations of motion for a steady spin show that the inertia moment is proportional to the square of spin-rate and reaches a maximum at 45 degrees angle-of-attack. The balance of pitching moments at low angles-of-attack occurs at low spin rates and at high angles-of-attack with high spin rates. This is the reason for the typical characteristics of 'slow steep' spins and 'fast flat' spins. Movement of the elevator adds an increment to the aerodynamic curve as shown in Fig.5. but normally, this is not of sufficient magnitude to unlock the balance of pitching moments.

Of prime importance for roll equilibrium is the balance of the aerodynamic contributions due to roll rate and due to sideslip. The inertia moment may be positive or negative depending on wing tilt angle - having a zero value for zero tilt. Figure 6 shows the typical variation of aerodynamic rolling moments with spin rate and sideslip for a given angle-of-attack. Note that, for a significant change in spin-rate, the rolling moments can be balanced by a modest change in sideslip angle. Movement of the aileron adds an increment to the rolling moment curve but the magnitude is normally insufficient to unlock the balance of rolling moments. Aileron deflection will result in a change in the equilibrium sideslip angle and may contribute a yawing moment, both of which will affect the spin and spin recovery.

The two largest aerodynamic yawing moment contributions for the low-speed aircraft of this example are due to spin-rate and rudder deflection, as shown in Figure 7; by comparison the contribution due to sideslip is small, and, for the case of zero wing tilt, the inertia contribution is zero. Since the rudder can alter the yawing moment curve appreciably, the key to unlocking the balance of moments in a spin for the example aircraft is therefore, to generate a large yawing moment with the rudder.

In order to highlight the major aerodynamic contributions, the wing tilt has been taken to be zero. The equations of motion for a steady spin show that in this case the rolling and yawing inertia contributions will be zero. Tilt angles -usually leading wing down - of five degrees can occur in a steady spin. Consequently the rolling and yawing moment balance will be modified and so, in any detailed analysis, the inertia contribution must be included.

Consideration of the balance of moments has shown for the low-speed basic training aircraft example that the spin rate and spin angle-of-attack are closely related and are determined essentially by the balance of pitching moments; that the sideslip is determined by the balance of rolling moments, and that although all three control surfaces may be effective in changing the balance of moments- and hence spin conditions- the rudder is the most effective means of unlocking this balance. For aircraft of substantially different inertia loading and layout this emphasis may change.

2.4 INCIPIENT SPIN AND SPIN RECOVERY

These two phases are characterised by the transition between two extremely different flight conditions. Upon entry the aircraft has low angular velocity, moderate linear velocity, constant potential energy, and is flying at low angles-of-attack. The transition through to the 'steady spin' involves an initial increase in roll rate followed by an increase in yaw rate giving a large resultant angular rotation; a small change in linear velocity and a constant reduction in potential energy, with the angle-of-attack increasing to large values.

The aerodynamic changes are equally dramatic and involve changes from attached to separated flow over large areas of the aircraft surfaces with consequent unsteady flow behaviour. During 'spin recovery' these changes are reversed with additional transients occurring due to the dissipation of angular momentum.

Although some progress has been made towards understanding the aerodynamic behaviour occurring during the spin, reliable methods for spin prediction do not yet exist. Even the methods for the prediction of steady spin behaviour only yield gross trends and so scale model testing is generally carried out where possible, in order to reduce project risks and to provide a basis for the flight development phase.

A discussion of the methods currently available for aircraft spin prediction including scale model testing is presented in Section 4.

3. HISTORICAL DEVELOPMENT OF SPIN RESEARCH

The following summary is based, in the main, on research publications from the U.K. and U.S.A. and in consequence may not give due recognition to developments in other countries. The summary emphasises the continuous efforts in spin research since the early days of flight and highlights the major developments in research methods. However space does not permit a discussion of the results and design information produced by those methods.

One of the earliest written reports on the spin is contained in the August 31st edition of Flight Magazine for 1912. The article refers to a manoeuvre carried out by Lieutenant Parke of the Royal Navy, and witnessed by Mr Berriman, the editor of "FLIGHT" and Mr Short of the Royal Aircraft Factory. The manoeuvre was referred to as Parke's dive.

Following this event only two spin accidents were reported prior to the First World War.

It is generally agreed that the first pilot to demonstrate a method of recovery from the spin was Harry G. Hawker, the son of a blacksmith from Moorabbin in Victoria, Australia. Sopwith, Hawker, and Sigrist launched the Sopwith Aviation Company at Brooklar ' in the U.K. in 1912 .

The earliest scientific measurements were carried out by Lindemann, Glauert and Harris at Farnborough and were reported in the British Aeronautical Research Committee publication series 'Reports and Memoranda' R&M 411 dated March 1918. (Bibliography 1915-1919/1). F.A. Lindemann later became Professor of Experimental Philosophy at Oxford University, then during World War II was scientific advisor to Winston Churchill. Lindemann noted that "the stresses are not dangerous in a proper spin" and also "Analysis and Experimental results indicate that this is a stable form of motion".

Leonard Bairstow, whose text book' Applied Aerodynamics' was published in 1919, suggested that "the manoeuvre known as spinning might be imitated in a wind channel by mounting an aerofoil so that it may be free to rotate about a horizontal axis". This technique was implemented by Ernest Relf and the results were reported together with a comparison with estimates using strip theory in R & M 618 (bibliography 1920-1929/3). A summary of the status of spin knowledge was made by the Stability and Control Panel in 'R&M 1000' in 1925, (bibliography 1920-1929/4).

In 1926 Professor B.M. Jones and Miss A. Trevelyan published a 'R&M' 999, (bibliography 1920-1929/5) entitled 'Step by step calculations upon the asymmetric movements of stalled aeroplanes'. The text reads "the detailed study of the few seconds during which an aeroplane descends from steady flight to a spin has been made in one instance and employed a skilled calculator for many months". We can guess that the calculations were carried out at about 0.1 Floating Point Operations per Second (FLOPS), which may be compared with current scientific computer speeds of 6 Mega FLOPS. A further indication of the tedious procedure is noted in the comment "At about midway through the calculation (about 1 second) a further series of wind tunnel tests had been completed and better aerodynamic data became available".

In October 1926 Gates and Bryant published a comprehensive survey on the 'Spinning of Aeroplanes' in which the equations required for calculating equilibrium spins were presented. (bibliography 1920-1929/8) also (Reference 1)

A major development in spin research was carried out by Irving and Batson at the N.P.L. between 1925 and 1935. They developed and used a continuous rotation balance in the 7 ft. No. 2 tunnel. These test provided aerodynamic coefficient data and a good insight into aircraft spinning.

A.V. Stephens, later to become the first Professor of Aeronautics at Sydney University, was involved during this period in full-scale and scale-model flight testing, at R.A.E. Farnborough.

Stephens early model experiments involved launching dynamically scaled models from a height of 80 ft in the Balloon Sheds at Farnborough. Later under the direction of McKinnon Wood he was concerned with the development of the 12 ft dia. vertical wind tunnel at Farnborough for testing dynamic models. The tunnel began operation in 1932 and a large number of configurations were tested in the facility.

In 1935 a third continuous rotation balance was commissioned at the N.P.L. However a somewhat disconsolate note appeared in the associated report. It states that "The Spinning Panel advised that theoretical work, could with advantage, be postponed in favour of the generation of more ad-hoc design data". Only one major study using the rotary balance appears to have been carried out at N.P.L. following this report.

At the Langley Research Center in the U.S.A. a simple spinning balance was fitted to a 5 ft vertical tunnel in 1931 and tests were carried out on wing auto-rotation during the 1930's. A 15 ft diameter vertical wind tunnel for testing dynamic models was commissioned in 1936 and the earliest results reported in 1939. This tunnel was replaced in 1941 by the current 20 ft diameter vertical spin tunnel.

The introduction of the dynamic model technique using vertical wind-tunnels permitted the testing of a wide range of configurations. Unfortunately it led to the termination of the more basic investigations possible with the rotating balance. The dynamic model technique provided data for the development of empirical design criteria upon which preliminary design estimates can be made.

Beginning in the mid 1970's a number of rotating balances were commissioned throughout the world to investigate aircraft high angle-of-attack and spin behaviour. These developments have led to a greater understanding of the aerodynamic behaviour of aircraft in these flight regimes. A brief discussion of these facilities and of current spin prediction techniques follows.

4. SPIN DESIGN AND PREDICTION TECHNIQUES

Figure 8, taken from bibliography 1980-1983/11 summarises the recommended approach to the prediction of aircraft stall and spin characteristics. The figure shows that stall and spin behaviour are still very important design considerations in general aviation and military aircraft and indicates that a large and varied amount of testing is required to predict, with confidence, full scale aircraft behaviour.

Figure 9 summarises the major spin prediction techniques currently available, their range of application, and the location of some of the major facilities.

Empirical design criteria for spin recovery would generally be augmented by more detailed information if available, on similar configurations, to improve the level of reliability. Although its application must be strictly qualified it still remains the only technique which does not require experimental test data.

As discussed in Section 3, the dynamic model and rotating model techniques were developed in the U.K. and USA during the 1920's and 30's. These are the methods most commonly used today for aircraft development programmes and were selected for use on the Australian Basic Trainer development programme.

Only two facilities are available in the Western World for dynamic spin model testing. These are located at the NASA Langley Research Center and at IMF Lille in France. The technique involves launching a dynamically scaled model into a vertical airstream and then recording on video the steady spin behaviour and spin recovery following actuation of controls. Analysis of the recording gives rate of spin, angle-of-attack and sideslip and spin recovery times for the given combination of pro-spin and spin-recovery control settings.

Rotary balances have been commissioned at a number of wind-tunnel facilities as indicated in Figure 9. At the Langley Research Facility and at IMF Lille the balances are both installed in the vertical spin tunnels and both dynamic-model and rotary balance programmes are carried out in the same facility. At other organisations the balances have been installed in conventional horizontal wind-tunnels. These balances have been used mainly for studying the high angle-of-attack departure problems of combat aircraft.

An unsuccessful attempt was made in 1950 to resurrect the rotary-balance technique, but the method did not become viable until the late 1970's when developments in instrumentation, data logging and computer analysis provided the required data rate and accuracy.

The capability to calculate 'steady spin' conditions from rotary balance data was revived by Dr. Bazzochi of Aeromachi in 1975, (bibliography 1970-1979/15) and by Tischler and Barlow in 1980 (bibliography 1980-1989/3), although the general procedure had been foreshadowed by Gates and Bryant in 1926 and had been employed by Bamber, Zimmerman and House at the Langley Research Center in 1935. This latter formulation was programmed by Bihrle in 1980 at the Langley facility. (bibliography 1980-83/15)

The merits of rotary balance testing for spin prediction are: Firstly that it provides aerodynamic force and moment data in coefficient form. Secondly, the model can be tested with components removed enabling their direct and interference effects to be investigated. Thirdly, the effects of modifications on the forces and moments can be determined. Finally, once the aerodynamic information is available the steady spin conditions for a wide range of centre of gravity, inertia, and altitude changes can be calculated using the steady spin equations of motion. Although the rotary balance technique does not provide all the information required to predict spin recovery, an indication of recovery control effectiveness can be determined and this, coupled with the insight afforded by the method, enables estimates of the recovery capability to be made.

The remaining four techniques listed in Figure 9 involve free-flight testing of scale-models. The drop-model technique using approximately 1/4 scale-models has been employed recently in the U.K. and U.S.A. for investigating the high angle-of-attack behaviour of combat aircraft, and has the potential to cover all phases of the spin. However, because of cost and substantial manpower requirements it only becomes viable for major projects.

While spin design requirements are extremely important for many aircraft, it is clear from this brief survey that spin testing facilities and spin research activities are confined to a small number of aeronautical establishments.

5. RECENT RESEARCH AT ARL

In 1984 ARL initiated a research task aimed at developing a mathematical model of the spin behaviour of a basic training aircraft design. This task is embraced within longer term aims of studying the dynamic behaviour of combat aircraft at high angles-of-attack.

Early computer models of spin behaviour were extensions of the conventional flight dynamic models which used static and oscillatory wind-tunnel data. A common problem in these models was their inability to reach steady spin conditions.

In 1954 an alternative formulation of the flight dynamic model was proposed by Scher (bibliography 1950-59)/13) which allowed for the inclusion of rotary-balance data. Since the rotary-balance data is measured during steady rotations representing steady spinning conditions the model gives more accurate predictions of the steady spin. As with a conventional model, this alternative formulation requires data for the forces due to oscillations about the steady conditions. However experimental methods for determining these oscillatory contributions in the presence of steady rotations are still being developed.

Because of this deficiency and the poor quality of the initial rotary balance data the alternative formulation has not been widely used.

In 1983 a comprehensive set of rotary balance data was measured on a basic training aircraft design in the NASA Langley Spin Research Facility in support of an Australian aircraft development programme. These data are being used in a flight dynamic model for the simulation of aircraft spinning.

In addition to the steady rotation data, information is also required on the aerodynamic forces occurring during the non-steady spin-entry and spin-recovery manoeuvres. Wind-tunnel methods for the measurement of these forces are not yet available and so simple aerodynamic estimation techniques have been investigated.

Figure 10 shows the span-wise wing-loading for a straight wing under steady rolling conditions. The results have been calculated using a simple bound vortex representation of lift and a discrete line-vortex representation of the wing-wake. Bound vortex strength is obtained from experimentally determined two-dimensional lift data and this together with the corresponding drag information enables the spanwise load distribution to be calculated. The model can be used to determine the variation in aerodynamic coefficients due to small disturbance about the steady rotation condition.

To provide additional insight into the nature of the flow at the tail of an aircraft during spinning a joint ARL/NASA wind-tunnel program has been conducted in the NASA spin test facility at Langley Research Center to determine the pressure distribution on the tail, fin and fuselage of a model during steady rotation.

An example of the test results is shown in Fig. 11. This programme provides aerodynamic details not previously available on the flow in the important regions of the tail of a spinning aircraft.

6. CONCLUDING REMARKS

Early research into aircraft spinning led quickly to an understanding of the main dynamic characteristics of spin behaviour but also identified the need for a greater understanding of the complex nature of the aerodynamic forces. The complexity arises from the large aircraft angular rates and hence large changes in onset flow conditions, and from the large areas of flow separation. Facilities were developed as early as 1926 for measuring aerodynamic forces on models during steady rotation, but these were abandoned in favour of the dynamic-model spin tunnel technique in an attempt to obtain more tangible design data. The dynamic-model technique has been extended to include a range of free-flight techniques, all of which provide information directly on the model dynamic behaviour, but provide very little insight into the aerodynamic characteristics. Since the mid 1970's new facilities have been developed to measure the aerodynamic forces on rotating models and efforts are being made to parallel these experimental results with theoretical and numerical analysis. With the rapid developments in computational aerodynamic design methods, the prospect of more reliable spin design prediction techniques can be foreseen.

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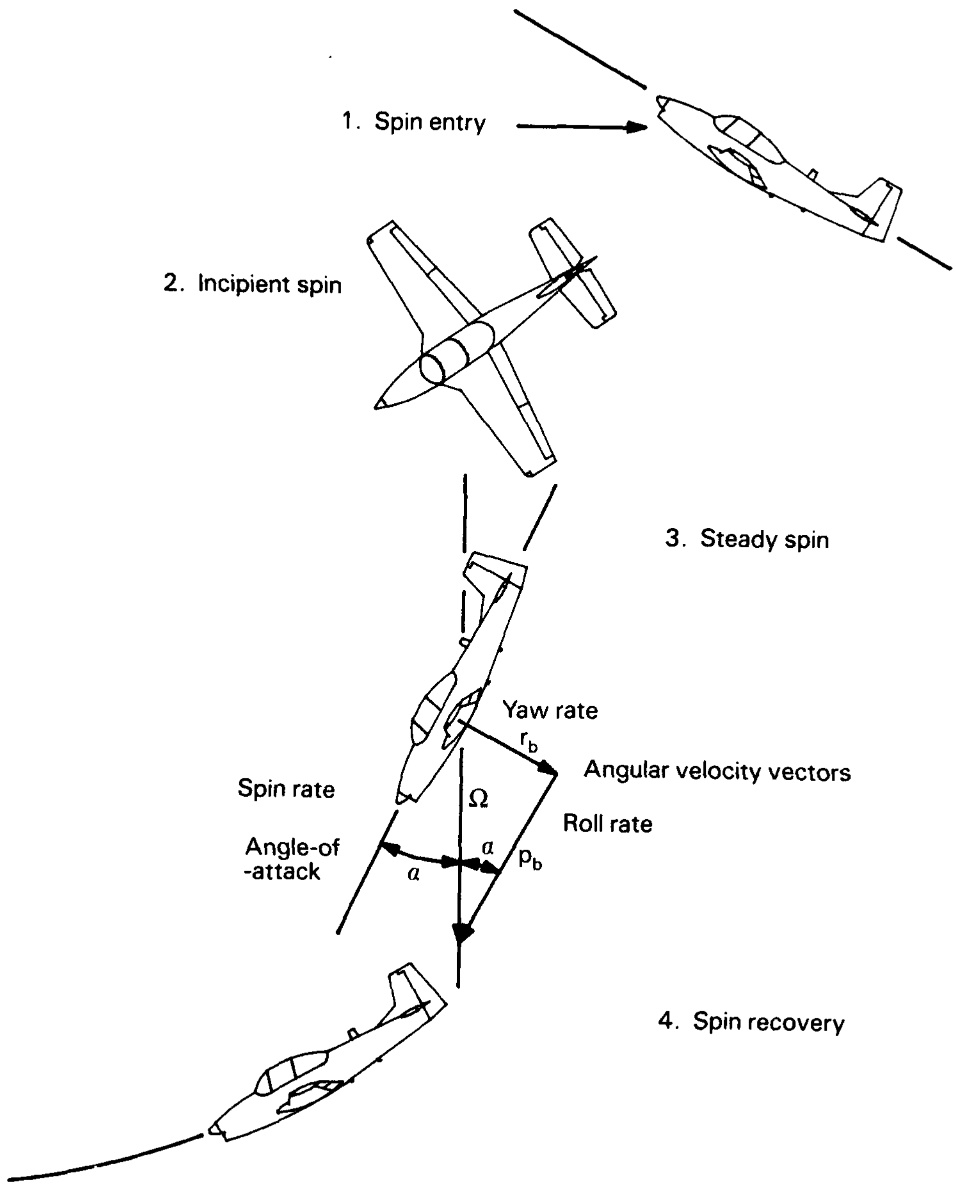


FIG. 1 THE SPIN MANOEUVRE

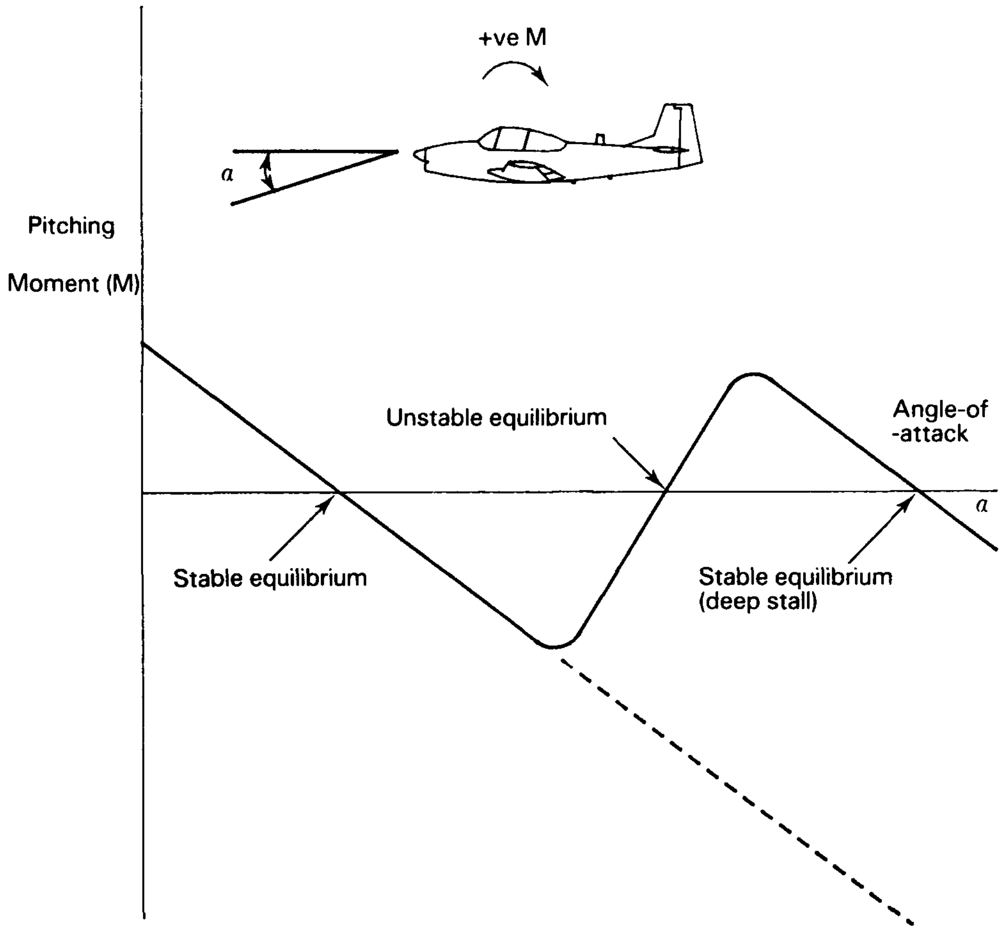


FIG. 2 LONGITUDINAL TRIM CONDITIONS

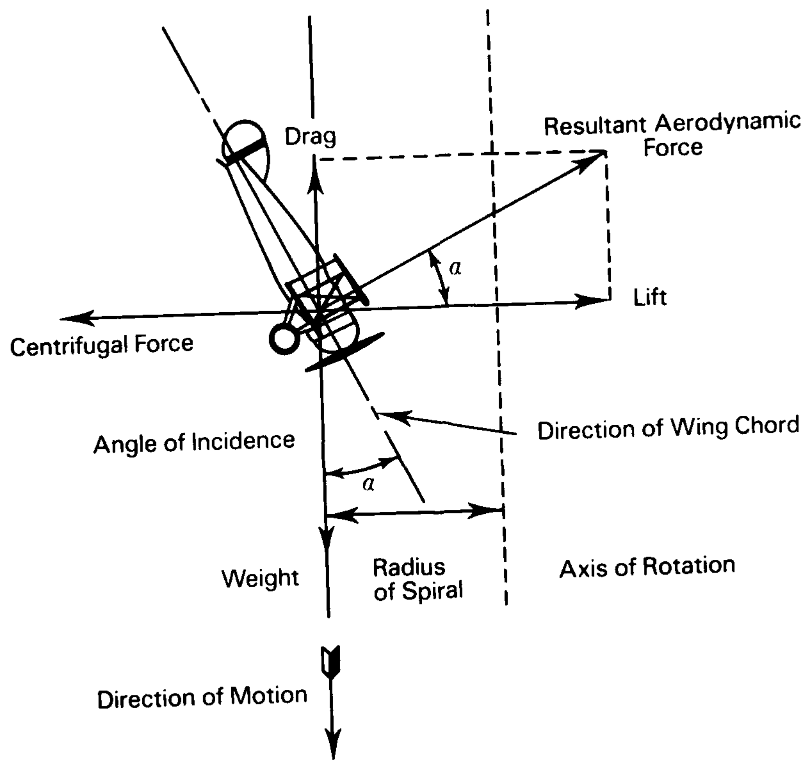


FIG. 3 BALANCE OF FORCES

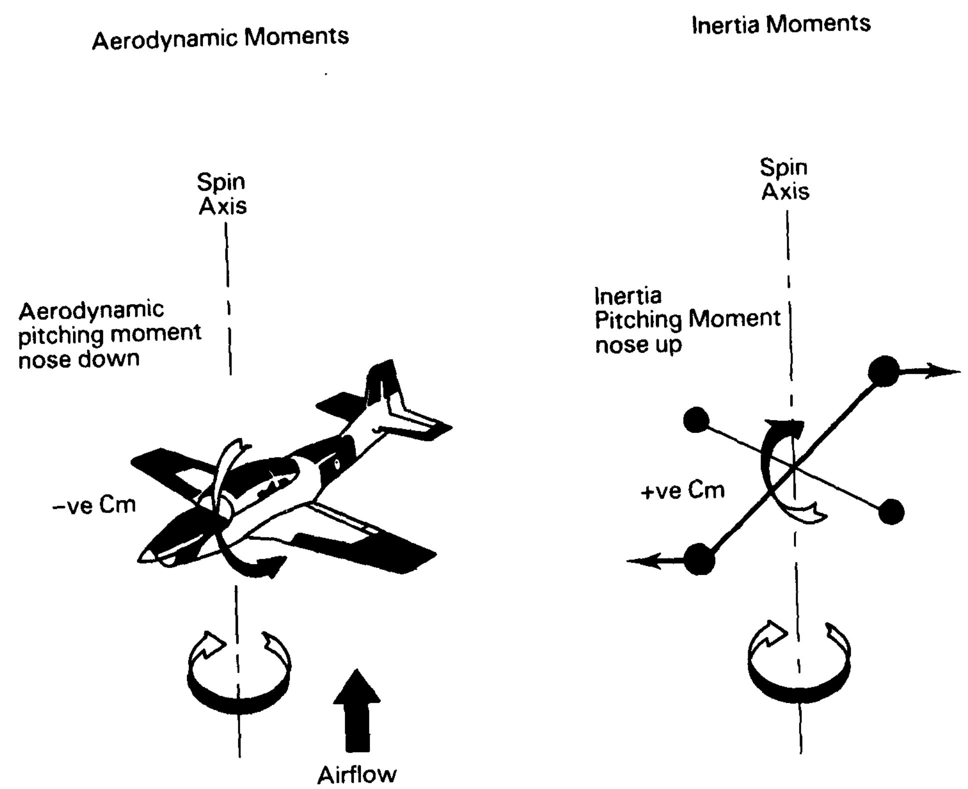


FIG. 4 PITCHING MOMENT CONTRIBUTIONS

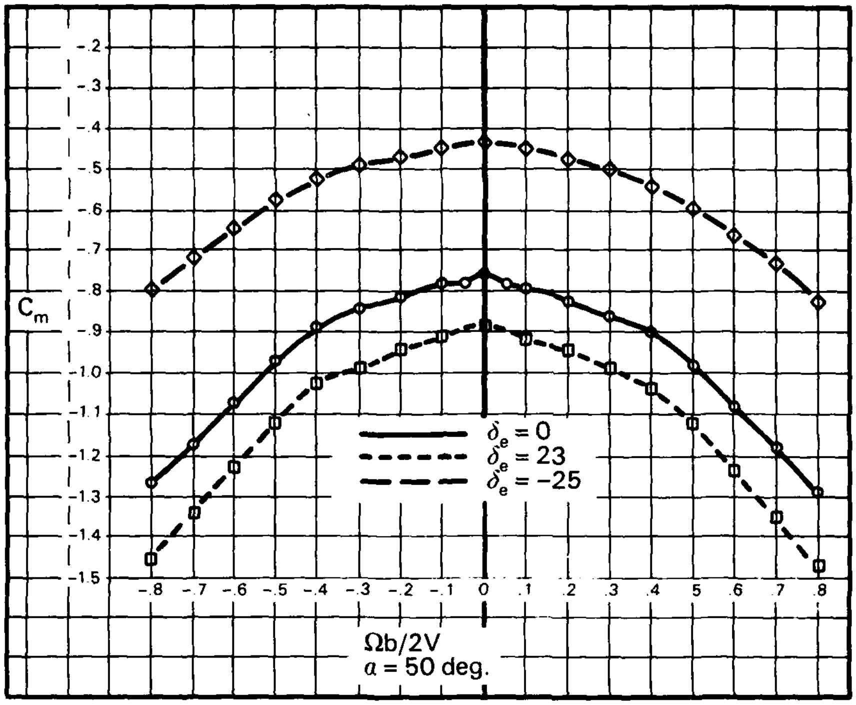


FIG. 5 EFFECT OF ELEVATOR ON PITCHING MOMENTS

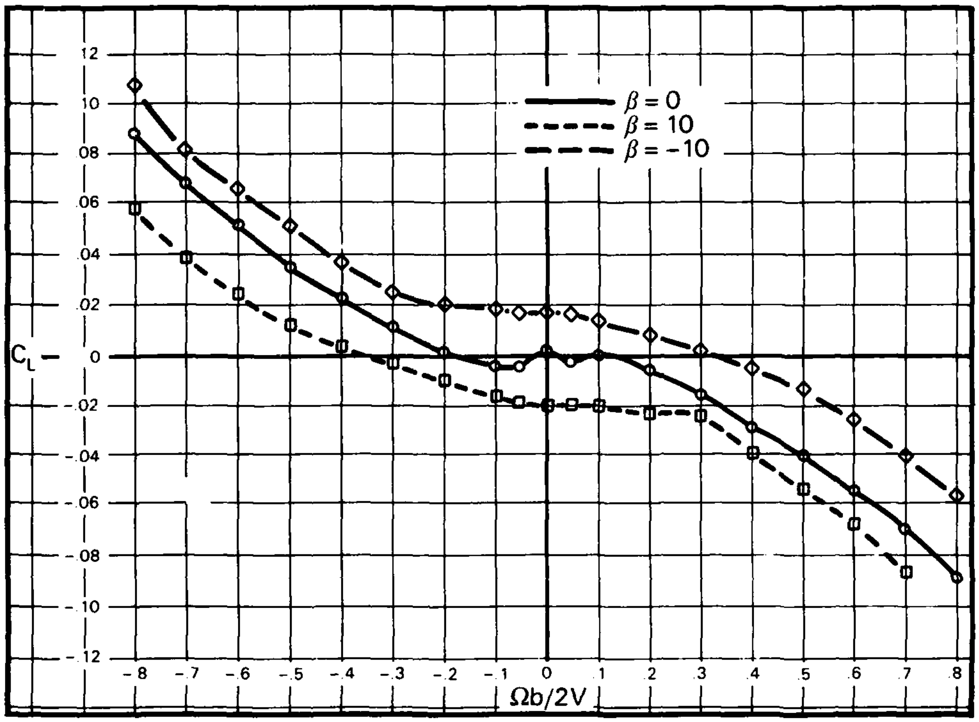


FIG. 6 ROLLING MOMENTS

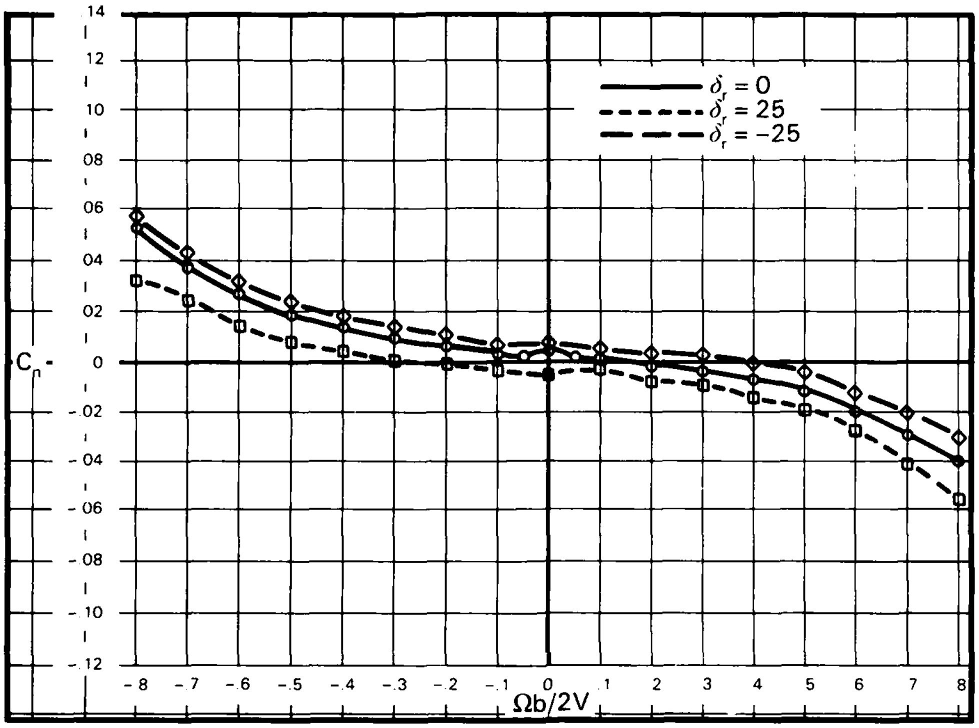
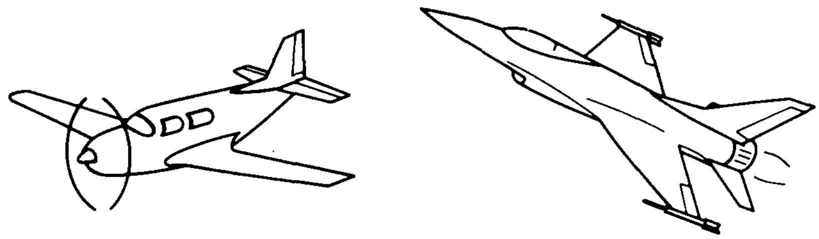


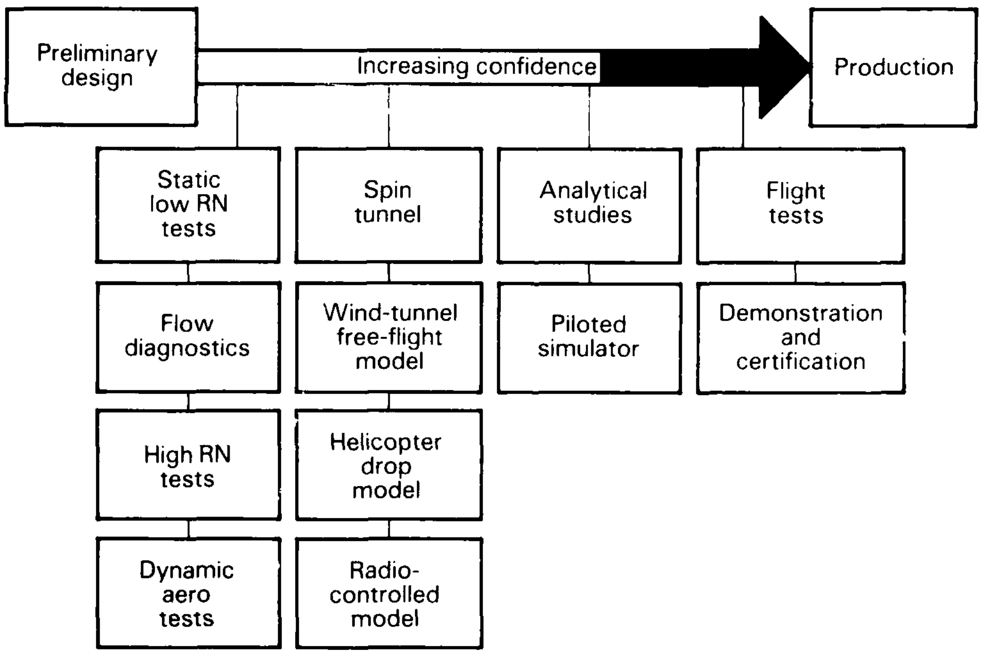
FIG. 7 YAWING MOMENTS



- Safety
- Pilot training
- Certification requirements

- Manoeuvrability
- Tactical effectiveness
- Safety

Impact of stall/spin characteristics on operational usage of general aviation and military airplanes.



Recommended method of approach for prediction and analysis of stall/spin characteristics.

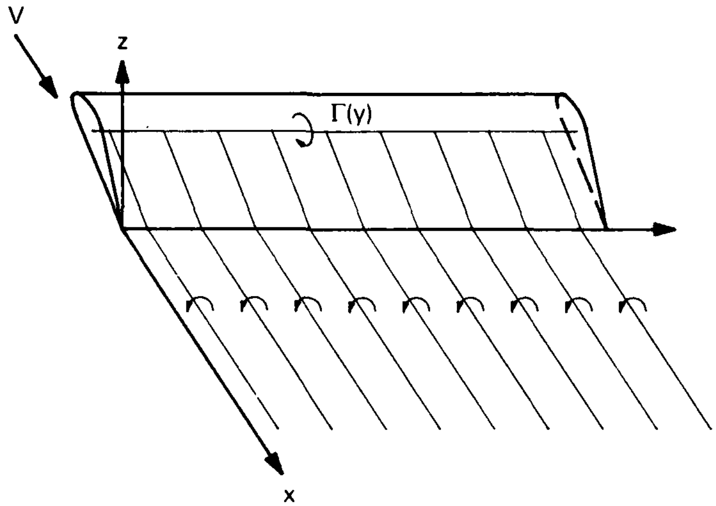
FIG. 8 PREDICTION OF STALL/SPIN CHARACTERISTICS

Spin prediction techniques

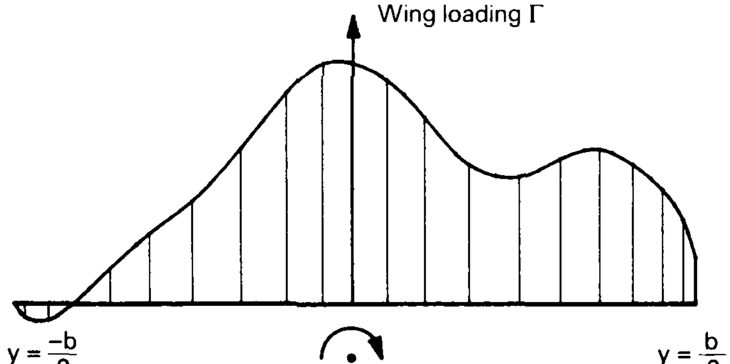
Technique	Spin entry	Incipient spin	Steady spin	Spin recovery
Empirical design criteria				
Dynamic model in spin tunnel			NASA Langley	IMFL Lille
Rotary balance technique	NASA Langley/Ames, Aeromacchi B. Aerospace RAE., IMFL Lille			
WIND TUNNEL (FREE FLIGHT)	NASA Langley			
Catapult model technique	NASA Langley, IMFL Lille			
Helicopter drop model	NASA, RAE, ARL			
Powered radio controlled model	NASA, Aeromacchi			

FIG. 9 SPIN PREDICTION TECHNIQUES

Line vortex model of rolling wing



Vortex line model from NASA
CR-2774



Roll rate $\Omega b/2V = 0.3$
Angle of attack $\alpha = 13$ deg.

Wing loading in steady roll using
experimental section-data

FIG. 10 WING LOADING DURING STEADY ROLL

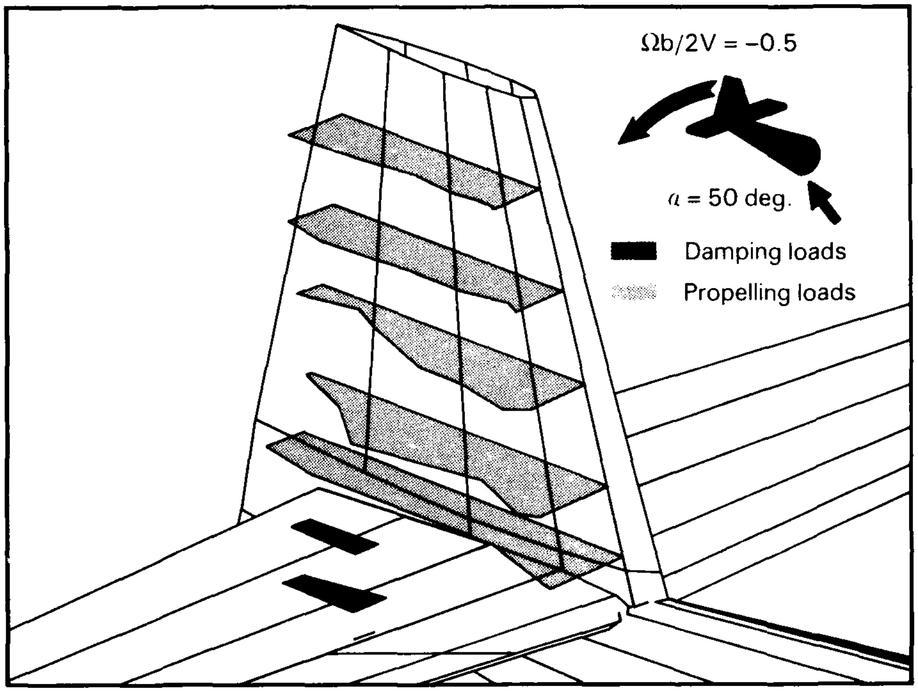


FIG. 11 PRESSURE LOADING ON THE FIN OF A ROTATING MODEL – NON-DIMENSIONAL SPIN RATE – 0.5, ANGLE-OF-ATTACK 50 DEG.

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16. ABSTRACT Aircraft spinning is an important area of design for general aviation and military aircraft, and has been so, since the early days of aviation. In many of the major aeronautical laboratories in the world, aircraft spinning has been the subject of intensive periods of research. However, the resulting design criteria are still only adequate for predicting gross trends in aircraft spin behaviour. To enable flight testing to proceed with confidence and to minimise modifications during flight development most major aircraft development programmes include extensive scale-model spin testing. In this paper, the development of these

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techniques and their application for spin prediction will be discussed. In current military aircraft stability augmentation systems add further considerations for high angle-of-attack and spin behaviour. These and future considerations of thrust vectoring for aircraft control at high angles-of-attack are outside the scope of this paper.

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